

AMRL-TR-66-122



AD 643239

ODOR CODING FOR MALFUNCTION DETECTION AND DIAGNOSIS

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AUGUST 1966

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AEROSPACE MEDICAL RESEARCH LABORATORIES
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

DEC 13 1966

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FOREWORD

This report was prepared by the Philco Corporation, Western Development Laboratories, Palo Alto, California, under Contract AF33(615)-2948, Project 7184, "Human Performance in Advanced Systems," and Task 718406, "The Development of Human Engineering Maintainability Design Criteria," for the Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories. Mr. Billy Crawford, Maintenance Design Branch, Human Engineering Division, Behavioral Sciences Laboratory, was the Air Force technical contract monitor. The report covers work performed from May 1965 to March 1966.

The authors are grateful to Mrs. Ann Knopf, Henri DePorceri, M. A. Picciano, and Miss Pat Campbell, all of Philco WDL, for their contributions of material used in the preparation of this report. Special recognition is due to Paul Atkinson, Dr. William Hagin, and Clair Cunningham for serving on the Philco Executive Review Board and providing helpful advice and criticism.

This technical report has been reviewed and is approved.

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ABSTRACT

The use of the olfactory sense for detecting and diagnosing malfunctions in equipment systems has been investigated. The literature on olfaction is reviewed and the data and data gaps relevant to equipment maintenance applications are summarized. With the literature findings as a point of reference, performance requirements for an odor-coding system are established and a taxonomic structure is synthesized for the purpose of developing specific odor-coding systems. A survey of equipment system applications leads to the conclusion that odor-augmented maintenance displays are both feasible and practical. Recommendations are made for a program of research and development leading to broad scope implementation of odor coding for malfunction detection and diagnosis.

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SECTION I

INTRODUCTION

The major categories of man's many sensory capabilities have been researched and considered for practical application in somewhat the following order of emphasis: visual, auditory, position and motion-sensing, somatic, and taste and smell (ref 37). A frequency histogram of actual applications to equipment systems would probably be more exponential than linear in appearance, with vision by far the most frequently used sensory mode.

It appears appropriate, therefore, to speak of the primary (frequently used) and secondary (infrequently used) sense modalities. While there have been occasional references to the desirability of exploring applications of the secondary senses in general and the olfactory sense in particular (ref 39), there has been no notable concentrated effort toward exploiting the seldom relied upon secondary senses.

However, recent interest in putting the secondary senses to work has stimulated study of what is known about these less well investigated senses, and how this knowledge can be applied to systems and operations problems with sufficient payoff to motivate developmental work. One of the secondary senses selected for special examination is olfaction -- the sense of smell.

Preliminary study had shown that a promising application for the sense of smell was in the detection and diagnosis of equipment malfunction. The lack of adequate cues and indications is one of the very critical deficiencies that makes maintenance a high skill level and time consuming activity. The occasional informal smelling of burned resistors, transformers, etc, in the detection and diagnosis of failures lends some credance to the notion of a formal odor code for maintenance purposes.

Odor stimuli offer two major advantages that make olfaction a prime candidate for maintenance cuing. First, this sensory channel is not overloaded, and, in fact, is most likely underloaded. Therefore, it has the capacity for transmitting large amounts of information. Second, odor has a pervasive action-at-a-distance quality that gives it a unique capability to serve as a maintenance signal. A technician could be attending to other stimuli in or out of the maintenance context, and still be receptive to odor cues whenever they may occur. With the development of a formalized procedure of odor coding, so that each represents a particular malfunction, maintenance could be considerably facilitated.

The organization of the sections of this report will follow closely the sequence of project work. The amount of overlap among study stages and the interplay among areas of content, however, preclude construing the report as a simple chronicle of development.

SECTION II

ANALYSIS OF LITERATURE ON ODOR CODING

Odor Characteristics

Odor characteristics assume a considerable degree of importance since they form the basis of the odor-coding system. Chemical source books comprise much of the background literature in this section, especially the divisions dealing with chemical suitability factors and amount of odorant needed to reach threshold. The diversity in methods of experimental study evolved as a critical problem; experimental variations precluded many attempts to relate results. Representative studies illustrate this situation and the parallel problem of obtaining constant stimuli.

Chemical Suitability Factors: Several suitability criteria were considered when selecting a set of odorous compounds amenable to an applied evaluation of odor coding. One primary criterion was the distinctiveness of odor quality. This is a most important criterion because each odor must be easily discriminated from all others in the set and from any naturally occurring odors in the environment. It would have been fortuitous if the olfactory research reviewed had produced a useable solution to this problem of odor quality. Unfortunately, no suitable set of discriminable odors was found. Engen's study of odor discrimination (ref 36) came somewhat close to meeting our requirements, but most of his odorants had to be rejected because of insufficient distinctiveness (eg, coumarin) or excessive volatility (eg, acetone). The basis for selecting distinctive odors, therefore, was of necessity a subjective combination of reviewing discussions of odor quality (ref 69), using the experience of a perfumery chemist, and actually smelling available odorants to obtain informal judgments.

A second criterion used was the threshold value of the odor. Man's sensitivity to the odor must be relatively high if the odor code is to be an effective signal. Although the data on threshold vary considerably among investigators and coverage of odorous compounds is not complete, adequate data were found to provide a first approximation evaluation of odor thresholds (refs 58, 96).

The third criterion concerned the propensity of the odorant to vaporize into the surrounding air and to diffuse throughout the environmental area. It is fundamental that the odor must reach the man if he is to detect and identify it. Two measures are relevant. Vapor pressure (refs 46, 70) is an index for the odor getting into the air, and the coefficient of diffusion is an index for the odor reaching the man in the environmental area.

The rate at which a gas diffuses is a function of its density. Graham's Law of Diffusion (ref 40) gives the relationship that the rate of diffusion of a gas is inversely proportional to the square root of its density or to the square root of its molecular weight. The law is stated mathematically in the form

$$D = K_1 \frac{1}{\sqrt{d}} = K_2 \frac{1}{\sqrt{M}}$$

where D is the rate of diffusion, d and M are the density and molecular weights of the gas, and K is the constant of proportionality.

Graham's Law represents only an approximation of the phenomenon of diffusion because the effects of the molecular forces of attraction, repulsion, and the non-ideal nature of the gases produce unaccountable deviations.

A plot of the average values of the diffusion coefficients for approximately 80 compounds ranging in molecular weight from 32 to 184 was prepared in order to organize the available data on the odorants to be considered for odor coding. An empirical expression was developed for the diffusivity of the vapors from the materials under standard conditions of temperature and pressure. The expression is given as

$$D_o = 10^{a+bM}$$

where D_o is the diffusivity in square centimeters per second and M is the molecular weight of the compound. The constants a and b have values of

$$a = -0.814$$

$$b = -36 \times 10^{-4}$$

The values of D_o are shown in Table I for the selected odorants. The diffusion coefficient plays an important role only in an environment which is totally quiescent (still air and isothermal surfaces). The introduction or production of convection currents will modify the diffusion process to a large degree.

The final criteria involved those aspects of the odorants that would present some kind of hazard. They encompass toxicity, flammability, corrosivity, and stability (ref 74, 89).

In bulk state, the odorants are low vapor pressure hydrocarbons or esters which are comparable to materials like cooking oils and lubricating oils in flammability. They will take fire and burn in air under certain

TABLE I

ODORANTS SELECTED FOR EMPIRICAL ASSESSMENT

Chemical	Empirical Formula	Mol Wt	M.P. °C	B.P. °C	V.P. at 20°C mm Hg	Threshold mg/liter	Coeff of Diffusion cm ² /sec
1. Anethole	C ₁₀ H ₁₂ O	148.20	22.5	235.3	0.058	1.4 x 10 ⁻⁴	0.0455
2. Benzaldehyde	C ₇ H ₆ O	106.12	-26.0	179.5	0.62	4.3 x 10 ⁻³	0.064
3. Benzyl Acetate	C ₉ H ₁₀ O ₂	150.17	-51.5	213.5	0.18	-	0.045
4. Bromstyrol (α)	C ₈ H ₇ Br	183.	7.	220	-	-	0.034
5. Carvone	C ₁₀ H ₁₄ O	150.21	-	227-230	0.078	5.5 x 10 ⁻⁴	0.045
6. Citral	C ₁₀ H ₁₆ O	152.23	-	228	0.058	3 x 10 ⁻⁴	0.044
7. p-Cresol	C ₇ H ₈ O	108.13	35.5	201.8	0.09	9.0 x 10 ⁻⁴	0.063
8. p-Cresyl Valerate	C ₁₂ H ₁₆ O ₂	192.0	-	-	-	-	0.032
9. Diphenyl Oxide	C ₁₂ H ₁₀ O	170.2	28	258.5	0.053	6.9 x 10 ⁻⁵	0.038
10. Ethyl Methyl Phenyl Glycidate	-	-	-	-	-	-	-
11. Eugenol	C ₁₀ H ₁₂ O ₂	164.20	-	254	0.018	3.9 x 10 ⁻³	0.040
12. Isoamyl Isovalerate	C ₁₀ H ₂₀ O ₂	172.26	-	194	0.70	8.0 x 10 ⁻⁴	0.037
13. Isobornylacetate	C ₁₂ H ₂₀ O ₂	196.28	29	225	0.165	4.4 x 10 ⁻⁴	0.031
14. Methyl Salicylate	C ₈ H ₈ O ₃	152.14	-8.6	223.2	0.105	1.2 x 10 ⁻¹	0.044
15. Phenyl Acetic Acid	C ₈ H ₈ O ₂	136.14	76.5	265.5	0.0033	-	0.050
16. Undecalactone (δ)	-	-	-	-	-	-	-

conditions. When the odorant is dispersed, however, the fraction of odorant in the air is so low that it is well below the flash point. The corrosivity of the materials is essentially negligible.

The odorants either in bulk or dispersed form do not represent a toxic hazard. Of the odorants considered, only a few of the halogenated compounds are relatively susceptible to light and air exposure.

Table I shows the 16 odorous compounds selected for preliminary applied assessment. Included in the table are the available measures that are pertinent to their selection and description.

Experimental Variables and Constancy of Stimulus: Major differences exist in the techniques followed during odor research, in methods of measuring responses, and in the chemical purity of compounds, thereby accounting for many of the discrepancies reported in such areas as threshold values and quality characteristics. A wide variety of devices and types of apparatus have been described for presenting an odorous stimulus, making use both of the simpler basic method, ie, sniffing from a container, and also of the blast technique, which introduces a controlled blast of air for some period of time (refs 30, 97). While the thresholds for the two methods do vary, the sniffing method seems to be adequate and more malleable than the blast techniques (refs 50, 51). Olfactometric techniques have been developed that are appropriate for group measurements where independent smelling points may be supplied with different odorous concentrations (ref 16), as well as olfactometers that deliver the odorant to an individual subject. Ough and Stone (ref 68) have developed such a device that delivers the odorant to a subject via a plastic hood, thus enabling natural breathing. While the olfactometer is generally more rapid and reliable in its testing, there is a loss of sensitivity when compared to the sniff method (ref 85). Deininger (ref 23) actually proposes an odor test room consisting of a 200 cu ft antechamber and a 500 cu ft examination room which would be completely equipped with meters and measuring devices, heated air blowers, and flushing equipment to remove traces of odorants.

There is also a problem in obtaining a consistent stimulus since variations exist in the purity of compounds (ref 99). Frequent disagreement over the relevancy of variables having a small effect on perception is reported. One such example is the effect of temperature, with one study (ref 4) reporting increased sensitivity for higher temperatures, and another study (ref 84) finding that the temperatures between 12.5° and 35° C do not significantly alter olfaction.

Another area of olfactory research which has been emphasized is that of obtaining some standard method for measuring subjective odor intensity. Both Weber's Law and Steven's Ratio Estimation methods have been applied, with the scaling for most of these tests being just noticeable differences (refs 41, 52, 56, 73, 77, 83, 86, 87).

Development of research is impaired by the present lack of uniform nomenclature for describing subjective odor response (ref 98). The necessity for accurate descriptions of odorous stimuli seems clear to virtually all researchers working in this area (ref 99).

The concern over reliability and degree of comparability consumes a considerable degree of the researcher's effort. Turk (ref 93) proposes the establishment of some control to insure consistent reliabilities in establishing odorant concentration, and suggests the following methods: classical laboratory comparisons, analysis of odorant solutions with modern instruments, the use of a tracer to appraise the role of the system in gas dilutions, or constant presentation of odor stimuli to the subjects. While it may be possible to consider any of these methods as the standard method, no such agreement is yet in evidence.

Odor Release

Releasing an odorant into the environment is an area not covered extensively by past research or applications. While several devices promise to be useful, few have been previously documented and therefore have not been discerned by this literature search. Past sources indicate that heat is one method for precipitating odor release, and since this seems applicable to our system, it is treated as being a critical consideration.

Surrounding surfaces that pick up an odor and distort it are being evaluated for their amenability to the scope of the system (ref 24).

Odor release comprises one of those considerations which, while not strictly relatable to olfaction, does fall under the auspices of consideration for an odor-coding system. The lack of fundamental literature is somewhat hampering, thus suggesting that applications must be described to evaluate the most efficacious technique for the specific system.

Heat Fluctuations Critical for Precipitating Odor Release: The release of an odorant may typically be precipitated by a fluctuation in the heat of a component. If the heat of some electronic entity exceeds its normal range, we can infer that failure is somehow involved, and maintenance action will be required. If the overheated part or area were known, the scope of such action could be substantially reduced.

To pursue this notion, we must be cognizant of relevant characteristic temperatures -- the ambient temperature of an enclosed equipment, the temperature of the surface area, the temperature of a specific vital component, etc. Even though the ambient temperature may not be the most universally accurate measure (ref 95), nevertheless, it is the most convenient and most nearly accurate parameter to use in heat measurement.

Gondor (ref 42) presents a formula to predict an increase in the ambient temperature for equipment when the power emitted within the equipment results in a temperature differential between the outside surface of the equipment and the outside temperature. He suggests that the temperature rise is a function of the amount of power dissipated (refs 42, 79). However, Elliott (ref 29) claims the relationship is not linear and warns that the heat rise of components inside the equipment depends on the thermal coupling to enclosure surface as well as inside ambient air temperature. Bibbero (ref 11) proposes that the calculations of ambient temperature requires a knowledge of the power dissipated inside the equipment and the rate of heat transfer to surrounding materials by such processes as conduction, convection, and radiation. If the current and heat are allowed to build up, they will eventually cause changes in the state of the materials, such as melting (ref 72).

Release Device and Materials: Investigation into potential release devices has produced a variety of materials which may be amenable to this system. In communications with wax companies manufacturing compounds for use in sealing and/or coating (refs 20, 7, 9, 19, 1), information was collected on materials operating at the temperature range most appropriate for various components. Waxes with melting points ranging from 30° to 130° C having an accuracy of $\pm 2^\circ$ are available. General temperature classifications enable the waxes to be compared within classes, and those with qualifications specific to the odor-coding requirements can then be segregated. Data in such properties as melting point, softening point, flash point, specific gravity, minimum and maximum temperature use, adhesion, and abrasion resistance are pertinent in this context.

Gelatin capsules provide another type of encapsulation device. It is possible to vary the melting point of soft gelatin capsules by using various humectants and plasticizers (ref 8). Specifically, the melting point can be determined according to how the heat would be applied (eg, a point of contact or general temperature rise, etc), the conditions of humidity, pressure, size, shape, etc. These factors would be dependent on the requirements of the specific odor-coding system.

Characteristics of Surrounding Surfaces: Metals and coatings differ greatly in their odor properties, and these surrounding surfaces may have an effect on the evaluation of odor qualities. As most surfaces pick up an odor, they modify and distort it so that in some cases the original odorant is unidentifiable. Data on such topics as odor pickup resistance and rate of release were collected on the odor properties of 25 surfaces (ref 24). Those properties displayed by non-metallic surfaces were generally similar to the characteristics of metals; however, some specific surfaces more nearly fulfill the requirements for an ideal material from the odor standpoint, eg, polyvinyl chloride -- acetate copolymer on steel, solid polymerized methyl methacrylate.

There is also evidence that natural odorants sometimes encountered in aircraft can interfere with perception of some warning odorants by untrained personnel. An odor detection study (ref 81) previously suggested pairing odorants with some of the volatile but non-odorous materials which are used on aircraft; however, no practical application of this notion followed. A study proposed by Bolstad (ref 13) would determine the relative outgassing and flammability characteristics of over 100 materials, including such examples as surface coatings, wire insulations, typing cords, molding compounds, adhesives, and coating compounds. While surfaces may occasionally cause distortion, most Air Force equipment is composed of steel or other metals not easily affected by odorants. Further, the odorants would be presented in concentrations strong enough to override modifications in perception, therefore surface surroundings do not present a major problem area.

Odor Dispersion

Both odor dispersion and elimination have long been important topics for air-conditioning engineers (refs 2, 57). Relationships among odors and various test rooms have been described for actual industrial or residential situations (ref 94), and are directly applicable to comparable military situations.

Diffusion rate of chemicals may be derived through an empirical approach and chemicals chosen whose diffusion rate would be consonant with a general dispersion system. Since air movement is characteristic of the great majority of environments, dispersion via air currents is more relevant than diffusion.

Air conditioning patterns bear implications for the location of the odor and its effect on the observer, ie, he must be "downwind" from the point of odor emanation. In most rooms, air must be distributed in such a way so that in the "occupied zone" from floor level to six feet, there are no horizontal or vertical drafts, yet there must be constant and controlled air motion, generally at a velocity of 15 to 25 fpm (refs 91, 92). It can be seen that the air would circulate in the room in such a manner as to effectively disperse the odorant to any area occupied by a technician.

Odor elimination can also be easily handled by removing the odor from the air via the air washing apparatus in air-conditioning equipment. A perceived odor results from some vapor mixed with air and most of these vapors dissolve in water (ref 91). For those odors not soluble in water, there is a wide range of filters that can be used for known classes of odors. Therefore, the air-conditioning mechanism will not only facilitate odor dispersion, but will also efficiently deal with elimination.

Perception and Identification

Threshold: Basic olfactory data are incorporated into the section of the literature search dealing with perception and identification. Fundamental studies and theories are reviewed and related to the use of the olfactory modality for detection.

Absolute Threshold -- Data on absolute thresholds can be found in several references (refs 6, 75, 58); however, as was previously mentioned, varying techniques were followed, thus making direct comparison of results somewhat difficult. One method is the initial presentation of a free water sample with progressive dilution of the odorous chemical until the odor is "just perceptible" (refs 6, 57). An alternate technique consists of presenting several stimulus bottles with only one containing the odorant, and requesting the subject to identify it (refs 21, 22). Recently, reports have described methods of threshold determination employing gas chromatography to quantify the stimulus at threshold (ref 58).

It would be most convenient if a usable deductive procedure were available for calculating threshold values of different odorants, following the type of method used by deVries and Stuiver (ref 25). The method outlines several steps to be followed in calculating the sensitivity of individual olfactory cells. Such measures as the time of presentation, flow rate, concentration, fraction of inhaled air passing through the olfactory slit, and the fraction of molecules hitting the epithelium are used to determine the threshold of one sensory cell. However, until such a definitive procedure is possible, it will be necessary to rely on empirical techniques with their small but disconcerting fallibilities.

Detection at High Concentration Levels -- The concept of consistent detection of odor is one that holds substantial relevancy in the notion of coding for maintenance. It is possible to analyze and measure differences in detection at, or close to, threshold and the majority of evidence in the literature is concerned with this problem (refs 6, 75, 82, 18, 17, 14). However, instead of dealing with detection at a near-threshold level, we must concern ourselves with a level where detection and identification are almost guaranteed. Behavioral variations such as a shift in attention cannot be allowed to influence perception, such as is the case at the 50% level (ref 82). Unfortunately, little background information was found in the literature that describes work done with high concentration levels. Since this area is of central concern to an odor-coding system, this may well be one aspect deserving future experimentation.

Threshold Variability -- Substantial evidence exists to suggest that while threshold variability within subjects is minimal, variations among subjects is large. In Bushtueva's work with reflex activity (ref 14), he discovered that olfactory stimulations in subliminal concentrations caused desynchronization in the EEG; however, the extent of the change varied

according to individual characteristics of the subjects. Other studies (refs 71, 49) report that although day-to-day variations for any given observer are small, there is a larger variation among observers. The specific odorant may be relevant to these results in that the ease with which the identification of the odorant is learned and retained may depend on the verbal association formed by that odorant for different observers (ref 59).

Since observations are relatively consistent in repeated trials, it is suggested that when taken in broad terms, data from one subject generally agree with information collected from other subjects (ref 9). Engen (ref 32) also reported variation in thresholds according to individuals, but relates them to the effects of training, as described in a later section of this report.

Concentration Curve as Affected by Range of Subjective Intensity -- Results obtained in judging odor intensity suggest that a relatively unpracticed person can identify correctly three levels of intensity of an odorant and that well trained persons can identify about four levels (ref 36). The more relevant finding for the purpose of odor coding is that the range of subjective intensity varies among different odorants (refs 90, 99). That is, one odorant may have a relatively low threshold with a flat intensity curve, while another odorant may have a higher threshold, but reach a greater level of subjective intensity. Engen (ref 34) presents evidence from experiments using amyl acetate and n-heptane; while the odor of the former seems to remain constant regardless of the portion of odorant used, the odor of the latter varies greatly at different concentrations, thereby concluding that a difference in the intensity curves may indeed exist.

The relevancy of this discovery is apparent to the odor-coding system, and may be another area in need of future research. In any system for malfunction detection, there must be a consistently high (.99) percentage of probability of detection, and a concomitant high degree of reliability in constancy of perception; therefore, odorants must be chosen that will meet both these criteria.

Masking and Adaptation:

Adaptation -- The olfactory sensory channel has considerable potential for gathering and relaying information; the pervasive and largely unused character of this sensory input would seem to recommend its use. A large part of the reluctance to accept odor as a reliable information channel is based on the concern that adaptation would obviate accurate identification of the odor. For the short periods of time which a technician would be required to respond to an odor, however, there is less danger of adaptation becoming a troublesome phenomenon than would be the case for other uses of the odor sense. There is even some evidence (ref 54) that the process of adaptation results in a gain rather than a loss of information during the shift from one level of sensitivity to another.

The degree of adaptation, rate of adaptation, and rate of recovery all vary among compounds (refs 65, 80). The rate and degree of adaptation are some function of the concentration of the odorant; as the concentration is increased, the absolute magnitude of adaptation increases. Strong odors exhibit adaptation in about 2 or 3 minutes, with resensitization occurring in about the same amount of time, and pleasant odors adapting more quickly than unpleasant ones (ref 64).

In working with supra-threshold intensity of odors, Schutz and Laymon (ref 76) discovered distinctive curves of adaptation and found high correlations between the two physical variables -- surface tension and vapor pressure -- and the rate at which adaptation occurred.

Both Engen and Moncrieff have found evidence substantiating cross-adaptation which occurs when adaptation to one odorant affects the sensitivity to other odorants. Adaptation can be further differentiated to homogeneous adaptation, where the odorants are quite similar, and to heterogeneous adaptation, when odorants are markedly different. Engen (ref 31) noted a definite cross-adaptation at threshold and supra-threshold levels; however, no single stimulus factor seems to consistently account for the degree of adaptation. By comparing types of cross-adaptation, Moncrieff (ref 63) found that homogeneous adaptation is much greater than heterogeneous adaptation, which is often quite small.

Masking -- It is possible for masking to occur when the intensity of one odorant passes that of another odorant, thus distorting the perception of the first. Masking and raising the threshold for perception of odors are seen as undesirable and detrimental effects of a detection system (ref 81).

Masking of odors is a problem that should be considered; however, under normal circumstances in an odor-coding system, it is unlikely to pose a major difficulty. In the majority of cases, only one odorant will be released to produce warning of a breakdown; therefore, it seems that adaptation may be a more critical parameter than masking. Of course, in areas with very powerful odors such as a high concentration of gasoline, special modifications will be necessary to insure detection of the warning odorants.

Theories of Olfaction: It is impossible to present a discussion of odor phenomena without touching upon the attempts to fit them into some theoretical structure. Amoore (ref 1) has caught public attention with his stereochemical theory which proposes that the geometry of the molecule is the main determinant of odor -- that the shape of the molecule must be complementary to that of some of the olfactory receptors. With this theory, he has attempted to provide an explanation for many of the already known olfactory phenomena, and others have incorporated this assumption into their theories (ref 62). It is the capability to relate data and to predict new findings which motivates theoretical development.

Beck and Miles (ref 10) indicate that a relationship may exist between olfaction and infrared absorption, leading to detection of an odor. Dravnieks (ref 27) bases his theory on ferroelectric effects, suggesting that once the olfactory receptors have detected the presence of molecules in the air, they will convey these observations to the brain in the form of electrical pulses, and differences will be recognized by the varying pulse frequencies. With several receptors, each "tuned" to a different absorption band, differentiation becomes possible.

The information theory of olfaction (refs 44, 45) is based on the assumption that the best way to understand the odor molecule's action on the odor receptors is to examine the informational capacity of the nervous system. Hainer (ref 45) proposes a 24-digit olfactory code where the receptor is either "on" or "off." When a certain combination of digits is stimulated, the brain, through a learning process, will recognize the odor. The learning process is seen as being of primary importance in the perception of odor.

Yet, even with many promising theories being proposed, there is little agreement on accepting any of them as a basis of research, prediction, or orientation. While acknowledgement is made of the fact that theories conflict (ref 26), the discrepancies may exist only superficially and, in the final analysis, may be reduced to energetics at the molecular level where they may actually supplement each other. Hahn (ref 43) suggests that comparisons may exist among methodological and conceptual problems, but feels the validity must be founded on experimentation.

For whatever reason, no general theory of olfaction has been developed. Since there is no common definition, we will examine the findings and uses of odor phenomena taken that they occur, with lesser emphasis on why things happen as they do.

Man Versus Machine: Before proceeding with the assumption that man will be detecting and identifying failure-associated odors, it is appropriate to consider whether a machine can do the job better.

As might be predicted, there is no decisive proof for either side. One study (ref 78) using gas chromatography with α and β ray ionization detectors reported the instrument detected concentrations of odorants as low as 10^{-15} moles. Another machine has been proposed (ref 28) which would relate surface phenomena to odor measurement on the assumption that a surface is influenced by characteristics of the outer molecular layers absorbed on the surface of the body (ref 66). Some method must yet be found to convert the changes in surface phenomena to changes in electrical circuits. Moncrieff (ref 61) describes an instrument where the air passes over a film coated thermistor which is sensitive to odors and measures heat changes through absorption. The similarity to the human nose is claimed to be striking and substitution of the machine for human detection functions is suggested.

Kendall (ref 55) presented four odorants to an expert panel and to a gas-liquid chromatograph. He discovered that while the human is able to discriminate between a large number of odor types and can characterize changes produced by mixtures of odorants, the machine can accurately detect small quantities of some chemicals. It may be well to follow the contention of Jellinek (ref 48) that the machine can best be used to determine chemical purity and man can more accurately compare odor qualities.

At the present time, man probably has the greater range of odor detection; however, it is likely that with continued technological improvement, the machine techniques will improve its relative effectiveness. For us, it appears most reasonable to pursue the investigation of man as both detector and identifier, since his presence would be required to operate the machine if not to be alert to odors himself.

Discrimination Among Odorants: Engen has established that 16 odors can be identified and discriminated without appreciable error after a small amount of training (refs 34, 33, 35). His evidence is in general agreement with Miller's notion about information processing (ref 60), but his number of odors falls considerably short of Hainer's information theory (ref 44) which proposes that the number of different odors that can be detected is larger than 10,000. The informal reports considered by Wright (ref 99) also suggest a greater number of odors than the 16 proposed by Engen.

Warning is given that when too many comparisons are demanded, relative rather than absolute judgments are made. Miller (ref 60) proposes arranging the tasks in a manner to enable the subject to make a sequence of several absolute judgments in succession.

Enhancing or Degrading Factors

Factors which are either beneficial or deleterious to perception and identification, such as practice or physical illnesses, are defined in greater detail. After only a short period, training enhances performance to a marked degree. Other considerations may be detrimental; however, they are relevant only in isolated cases, and even then do not seem to have a large effect.

Training: Performance in perception and identification of odors can be substantially enhanced as a result of training and instruction, consisting of such things as explanation of the method of evaluation, discussions to clarify qualities of odors under consideration, and an examination of samples (refs 15, 5). Samples must be coded and presented in identical containers. The number of samples to be evaluated should be kept below a limit of fatigue.

In forced-choice testing, thresholds were appreciably lowered by practice and by changes in subjective criteria, manipulated through instruction (ref 32), suggesting that practice and instruction can be as important to the final results as the method of measurement used. Regardless of which system is eventually used for classifying odor, learning is a central parameter in the perception and identification of odor (ref 45).

It is well established that man could be trained to use his olfactory capability to a much greater extent (ref 80). With training, not only the ability to identify odors, but also the differentiation of intensity levels of odorants can be improved.

Physiological Considerations: There are probably very few physiological conditions which limit the ability to accurately detect odors. Normal illnesses, such as colds, sinus infections, etc, may affect the olfactory channel (ref 99). It has been suggested that at these periods acuity may actually be increased, however the congestion limits accessibility of odor molecules to the receptor area. A simple decongestant may well solve the problem -- in addition to increasing acuity, it is beneficial for the observer.

Only a very small percentage of the population can actually be designated as having anosmia or parosmia (refs 47, 88, 67). According to Amoore,¹ who is currently working with partial anosmiacs to develop a theory of odor primaries, complete anosmia occurs with a frequency of less than one in a thousand people and can usually be ascribed to some earlier injury or illness. Parosmia, selective odor blindness to specific odors or odor groups, appears to be a normal curve phenomenon with about two per cent of the population falling two standard deviations below average threshold for an odor. Acuity does go down somewhat with age, and smoking was also shown to have a small but statistically significant effect deleterious to olfactory sensitivity (refs 3, 53). Hunger cycles show conflicting results when compared with olfactory threshold (refs 38, 77), but in all cases, the effects are small and apparent only in few individuals.

Summary

Olfactory theory does not yet provide an adequate basis for selecting a set of maximally discriminable odors or predicting with accuracy all the parameters of perception. The likelihood of developing a useful theoretical structure is low for the near future, but available data provide useful, albeit not entirely complete, answers to the problems of odor coding for malfunction detection.

The number of odors that can be easily discriminated as part of an odor code is dependent on a number of factors including the quality and intensity of the odorants and the conditions of familiarization and usage. Nevertheless, it appears entirely feasible that at least 16 odors can be used with an essentially negligible amount of training. The 16 odorous compounds recommended earlier in this section will have to be tried out in

¹ Amoore, J. E., personal communication, 1966.

a simulated maintenance environment to determine if any adjustments are necessary. Inasmuch as little threshold research has been conducted at concentration levels that assure perception without introducing problems of odor elimination, it will be necessary to determine empirically the optimum levels of odor concentration by varying the amount of odorant released into the environment.

Of two major factors that are potentially disruptive to an odor code, masking and adaptation, the more critical appears to be adaptation. The criticality of masking can be reduced by using distinctive odors in sufficient concentration to overcome any likelihood of odor interference. While degree and rate of adaptation vary among odorants and for different concentration levels, there are not enough data to go beyond the generalization that adaptation occurs in about 3 minutes and recovery takes about the same amount of time. If any of the 16 odorants selected do not have relatively long adaptation times, it will be necessary either to try substitute odors or to accept a 3 minute period of detection and identification for maintenance odor coding.

SECTION III

PERFORMANCE REQUIREMENTS FOR AN ODOR-CODING SYSTEM

General Requirements

The performance requirements will be stated in terms of and be validated through operational testing procedures rather than analytical computations of diffusion, volatility, etc. The following performance requirements are based on operational testing using operational equipment, appropriate container and trigger mechanism for the odorant, and realistic equipment failures in an air-conditioned room in which the air in the room is changed every 12 minutes with a temperature of 20 degrees centigrade. This temperature is typical for manned operational conditions and the 12 minutes is derived from the 5 air changes per hour requirement for personnel areas.

Specific Requirements

At least 16 odorants will be available for selection in any particular odor-coding system. In some applications, only failure detection will be required and therefore only one odorant would be used. The best experimental data available indicate that man can easily learn to discriminate 16 odors, although the number may turn out to be considerably higher with longer or better training procedures.

Each odorant must be discriminable from all other odorants used when tested as described above at a distance of 15 feet from the odorant container (probability of .99). Fifteen feet has been found to cover over 95 per cent of operational situations in the Satellite Control Facility (SCF), which is a typical Air Force installation. The probability of .99 has been chosen to guarantee successful perception. If odor coding is to become an acceptable maintainability technique, it must be highly reliable to instill confidence in user personnel.

Odorants must be high in attention-getting qualities and approximately equal in ability to gain attention. This requirement is self evident. In addition, odorants in any odor-coding set will be easily distinguished one from another.

Sufficient odorant must be used so that it can be detected and identified at a distance of 15 feet, 4 minutes after initial release, when tested under the operational conditions described above (probability of .99). Four minutes was selected because this time is an upper estimate for dispersion time and because what little data there are available indicate that a technician standing near the equipment may adapt to the high strength odor in about 4 minutes.

If the odorant is stored under pressure, the mechanism must be constructed such that the release of odorant is metered to such an extent that it can be detected at a distance of 15 feet, 4 minutes after initial release when tested as described above (probability of .99).

The odorant must be such that it will be evacuated from the air in 16 minutes under the conditions described above. With a complete air change every 12 minutes plus the 4 minute dispersion time, this 16 minute requirement will be obtainable, so long as dynamic energy of the odorant molecules is equal to or greater than that of air.

The size of the entire malfunction detection and odor release device must be such that no modifications need be made to the equipment except provisions for mounting the mechanism. This is an initial requirement that has been set to obtain initial acceptance of the odor-coding technique. If the technique proves its apparent value, it may become worth the cost of mounting in racks, cutting into equipment ventilation ducts, etc.

SECTION IV

ODOR-CODING SYSTEM TAXONOMY

Introduction

By dictionary definition, a taxonomy is a set of principles for classifying some population, or the classes by which the population members are related in meaningful ways. The critical part of this definition is the phrase "related in meaningful ways." Even more to the point is the phrase "related in useful ways." If all the ingredients, their environments, and criteria for an odor-coding system can be described in categories that relate one to another in meaningful and useful ways, the taxonomy thereby created becomes a useful tool for developing and evaluating effective odor-coding systems. It is this sort of taxonomy that is proposed as part of the effort toward successful implementation of odor coding for maintenance.

In developing a taxonomy in the form of a conceptual model for odor coding, a distinction must be made among three possible points of view: (1) the sequence of events taking place in an odor-coding system; (2) the considerations and activities of the researcher; and (3) the considerations and activities necessary for particular design applications. All the points of view have one thing in common, ie, the maintenance man and his activities. The sequence of events emphasize the maintenance activities, the research emphasizes the "man" aspects of maintenance in the development of an odor-coding system, and the applications of an odor-coding system by the designer considers both the maintenance man and his activities.

Although there is substantial amount of overlap among the content covered from the three points of view, the optimum progression of content coverage differs considerably. This will become apparent as the different portions of an odor-coding system are discussed, first in one context and then another. The sequence of events is listed first here, because it can set an orienting goal for the researcher and establish a first approximation sequence for his considerations and activities. These activities must be oriented toward the design and implementation parameters of an odor-coding system. The researcher does not, however, provide all the information and parameters for detailed design applications; only engineering development will provide designs with specification type of information for instrumentation.

The objective of the following discussion is to present both the researcher and engineering developers with a framework for arriving at information necessary for implementing an odor-coding system. This approach is reflected again in a later discussion which summarizes the necessary research for implementing an odor-coding system and outlines the steps necessary to arrive at a point where "handbook" type data can be used to write odor-coding system performance specifications and permit designers to accomplish the specific application.

Overview of Taxonomic Approach

Figure 1 shows a sequence of odor-coding system events in block diagram form. In examining this diagram, the block representing functional or physical equipment entities should be considered as a starting point. Although its selection is somewhat arbitrary, it is convenient to begin thinking in terms of an equipment referent. Some physical or functional entity of an equipment (eg, a resistor) may undergo a breakdown process (eg, a short). At this point, we consider two blocks of breakdown effects. One represents the set of effects which is used to obtain failure indications by conventional indicators such as meters, lights, and test equipment. The other represents the set of breakdown effects which can be used for an odor-coding system of failure indication. The two sets are not mutually exclusive. Any effect which can be used to turn on a light or cause a meter deflection can also be used to release an odor if we are willing to pay the price imposed by the required device.

There are two reasons for making the distinction. First, it will be necessary to establish the detection and diagnostic information provided by conventional indicators and procedures as part of evaluating the contribution to maintenance by odor coding. Second, the kinds of breakdown effects considered in the "conventional block" will tend to be characterized in terms of the operational functions of the equipment (ie, the kinds of things described in the theory of operation section of a technical manual). The kinds of breakdown effects included in the "odor-coding block" will tend more toward the side effects of equipment operation such as temperature change.

The breakdown effect relevant to odor coding can be described as activating some trigger (eg, meltable wax) on some release device (eg, a wax capsule) that contains an odorant. The ambient or nominal conditions will need to be considered when setting the value of the breakdown effect which will activate the trigger. The dispersion of the odor from the equipment and throughout the technician's area to detection and identification threshold for perception is dependent on the equipment environment (eg, size of area and air movements).

Once a perceptable odor is introduced, a technician can detect trouble and derive diagnostic information about the equipment referent which will fail, is failing, or has failed. This information closes the loop in Figure 1 back to the physical or functional entity of the first block. It also is relatable to that information which can be obtained by conventional indicators and procedures. An odor-coding system must either supply additional information or supply it better, or redundant information when it is considered necessary.

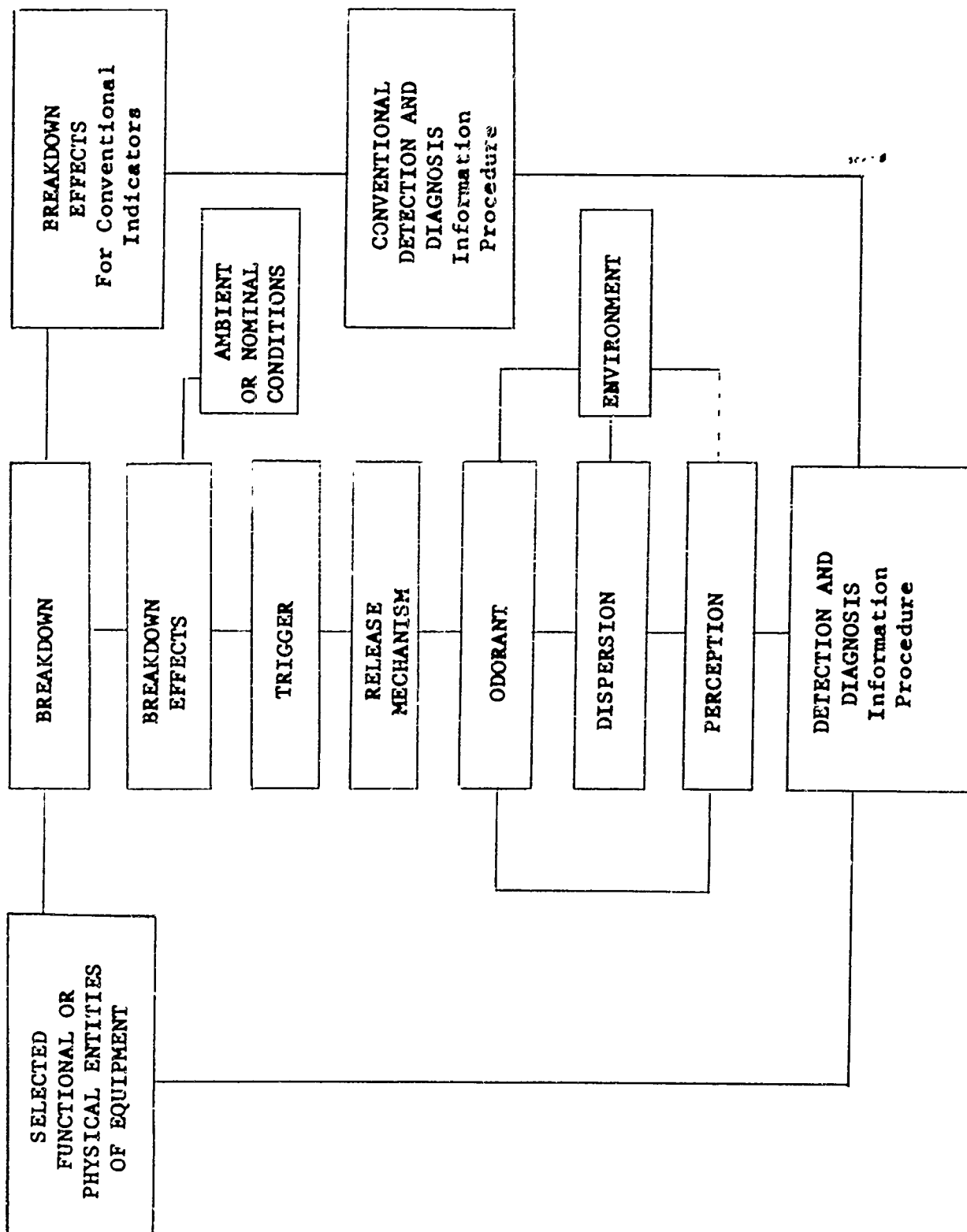


FIGURE 1
ODOR-CODING SYSTEM BLOCK DIAGRAM

Discussion of Matrices

The gross conceptual presentation of relationships pertaining to an odor-coding system has provided preparation for the next level of more detailed considerations. These considerations bring us further into the framework of the researcher's activities and closer to the activities of the designer who must eventually pattern specific odor-coding systems for maintenance.

The conceptual device selected for this development is the matrix -- not one matrix, because the variables to be related are many; but a series of matrices. A few words about the possible uses of matrices should help clarify how we are using them. One form of use may be characterized as a set of "sequential matrices." In this case, variable A is paired with variable B, B with C, and so on, until the relationship between any two variables may be examined by tracing through the sequence of matrices.

Matrices may also be used to show how several variables are relevant to different categories of some other variable. Therefore, a set of "differential matrices" is useful when one variable is related in different ways to different variables. The cells of the matrix format may be used to indicate several different kinds of relationships such as "may be used with" or "has an effect on," or they may present the numerical values of a quantified relationship.

Matrix Cell Relationship

All of the described matrix uses have been applied as appropriate, resulting in a mixed series. The odor-coding system blocks of Figure 1 have provided the variable headings for these matrices, and the relationships among the blocks have provided a basis for the more detailed relationships described by the matrices.

Major Problems to be Solved

Two major questions that become apparent when the matrix parameters are examined concern the equipment entities that are to be tagged with odors and the odorants that are to be used for this tagging. They are major questions because the number of potential alternatives is large. The problem implied by the question, therefore, is to reduce the number of alternatives that must be treated individually. The technique for accomplishing this reduction is based on the notion that relationships between parameters having a restrictive set of alternatives and parameters having an excessive set of alternatives can be used to define manageable categories for the excessive set.

Equipment Entities: The problem of specifying equipment referents demands special attention. At one end of the equipment dimension, we have the problem of considering general classes such as electronic, mechanical, etc. At the other end, we have the problem of considering the smallest

unit of description for equipment such as resistor, camshaft, etc. While an exhaustive enumeration and classification of all equipment systems and their different levels of subassemblies down to the smallest piece part might serve some useful purpose, the task would be overburdening and unending and the product would be unwieldy.

There are shortcuts for classifying equipment, but it appears especially efficacious to delimit the alternatives by considering only those which are amenable to other aspects of the odor-coding system. It is in this respect that the starting point in our block diagram was referred to as being arbitrary; other blocks may be considered as partial determiners for what was considered to be the "first" block.

The equipment problem is approached from two points of view. One concerns the selection of equipment items for odor tagging that will provide useful detection and diagnostic information. The other involves the technique for the release of odors by equipment item breakdowns. That is, before an equipment item can be used for odor coding, there must be both a technique available for effecting release of an odor and some information value to be gained by using the technique.

Release Device/Breakdown Effect Matrix -- Figure 2 shows a complex sequential matrix covering release device components and equipment breakdown effects.

Release Device. It is appropriate to examine analytically the general features of an odorant release device and to establish a terminology for describing these devices. A release device is conveniently construed as consisting of a trigger mechanism for sensing the breakdown effect and a container for holding the odorant until the trigger causes release. The trigger mechanism can best be described as having two components: a breakdown effect sensor, and a release action that liberates odor from the container.

It is necessary to have a terminology of sufficient dimension to encompass a wide range of possible applications. The need for specificity found in this matrix is not the same in all cases, eg, in the case of melting wax, sensor, release action, and container could be combined into one concept. However, in order to deal adequately with a more nearly complete scope of odor coding applications, it seems mandatory to have a nomenclature such as this one that will clearly differentiate and describe the separate functions.

The release device/breakdown effect matrix shown in Figure 2 illustrates the conceptual parts of a release device and shows the sensors, release actions, and containers that have been considered to be feasible. Each matrix cell marked with an X represents a release device. Each of the sensor and release

RELEASE DEVICE														
		CONTAINER			CAPSULE									
		CANISTER	COATING											
TRIGGER MECHANISM		RELEASE ACTION												
SENSOR		DIAPHRAGM RUPTURE	MECH. VALVE	SOLENOID VALVE	FRICTION	HEATER/HEAT	HEAT DIRECT	DIAPHRAGM RUPTURE	MECH. PUNCTURE	SOLENOID PUNCTURE	HEATER/MELTING	MELTING DIRECT	DISSOLVING	
BREAKDOWN EFFECT	TEMPERATURE		X		X					X				
												X		
								X						
			X						X					
			X						X					
				X			X			X	X			

FIGURE 2 - RELEASE DEVICE/BREAKDOWN EFFECT MATRIX

action combinations indicated by the marked cells constitutes a trigger mechanism. The type of container shown above the marked cell, in combination with that trigger mechanism, completes the description of a release device.

While the release devices represented in the matrix do not exhaust all possibilities, they provide an adequate set of usable techniques for releasing odorants and illustrate how the matrix approach can be used to treat systematically the problem of conceiving devices. There are additional detailed considerations to be made when configuring a release device for a particular installation which are beyond the scope of the general matrix presentation.

Breakdown Effects. The portion of the matrix of Figure 2 that juxtaposes breakdown effects and sensors rounds out a matrix sequence for relating release device components to categories of breakdown effects. It is possible to begin with a breakdown effect and quickly determine the basic ingredients for an appropriate release device: scan the matrix rows across from the breakdown effect to find the marked cells indicating pertinent sensor/release action combinations as trigger mechanisms. Any one of the indicated trigger mechanisms can be considered for use. Deciding on one particular mechanism will involve considering the suitability of the odor containers associated with these mechanisms.

Breakdown Effect/Equipment-Breakdown Matrix -- The most apt description of equipment breakdowns which are amenable to odor coding is by this definition: those equipment items which, when undergoing failure, produce a breakdown effect that can be detected by the sensor of a release device. This becomes a useful and operational definition when applied to a specific example where the amount of breakdown effect is quantifiable and the selectivity of the sensor is specified. This information is needed by the design engineer to fulfill his job of putting together a workable system. Inasmuch as there has not been any previous emphasis on assembling such detailed information, the task remains to provide the engineer with enough data for making accurate decisions. Statements about the range of applicability in as quantified a form as possible are presented in a later section of this report. The recommended nature of the matrix format that will eventually be used is shown in Figure 2. Since emphasis should be given whenever possible to detecting the incipient failures before they result in a loss of operational capability, breakdown effects before, during, and after a failure occurrence are called out separately.

Selection of Odor-Coding Referents -- The addition of odor coding to conventional, already established detection and diagnostic procedures suggests that, in the final analysis, the utility of odor coding be

evaluated in terms of those procedures rather than terms of percentage of diagnostic coverage or reduction in uncertainty. The latter kind of measures provide in part the basis for determining what parts of a conventional procedure can be bypassed or are provided with redundancy. It is necessary, of course, to consider a specific equipment and its specified maintenance procedures before the amount of reduced maintenance time can be estimated with any accuracy. This endeavor is properly part of developing a maintenance plan for an equipment system.

It is possible, nevertheless, to make certain generalizations about the savings that can be expected from an odor-coding system. These statements will be presented in Section V of this report.

Detection/Diagnostic Coverage Matrix -- It is possible to present in matrix form a convenient guide for use while estimating the amount of detection coverage and diagnostic power. Whether the estimate will be gross or fine, or a precise prediction of detection and diagnostic capability, will depend on the thoroughness of the maintenance analysis performed.

Figure 3 shows a recommended matrix format with number of used odors on one dimension; and on the other dimension, the average percentage of breakdowns represented by each odor. The product of these two values can be read in the appropriate matrix cell to find the percentage of failure detection coverage. The number at the top of the column gives an approximation of the degree of fault isolation expressed as a percentage of all possible breakdowns. If this figure is divided by the average number of failure modes per equipment item, an approximation of fault isolation power is obtained in terms of percentage of total equipment entities.

It should be re-emphasized that a most usable measure of utility for any odor-coding application is obtained by determining what steps can be eliminated from the checkout (preventive maintenance for detection) and diagnostic procedures ordinarily specified for the equipment system. Gains in equipment availability and reductions in maintenance time and expenditures are the prime considerations to be traded off against the design implementation and training costs of odor coding. Without a thorough maintenance analysis, the worth of odor coding (or any other aspect of maintainability) will never be known. Such an analysis with experimental validation of principles and techniques is recommended in Section VI.

Odorant Selection: As discussed in the literature section of this report, there are several characteristics of odorants that concern their selection for an odor-coding system. These characteristics may be categorized according to the aspects of the odor-coding model to which they relate: the container of the release device, dispersion and elimination of odor, and the perception of an odor.

PERCENTAGE OF BREAKDOWNS
WHICH WILL TRIGGER A GIVEN ODOR

		1	10	25	50	100
NUMBER OF ODORANTS	1	1	10	25	50	100
	2	2	20	50	100	
	3	3	30	75		
	N	N	10N	25N	50N	100N

FIGURE 3
DETECTION/DIAGNOSTIC COVERAGE MATRIX

Container and Odorant -- The odorant characteristics of (a) light sensitivity, (b) reactivity, (c) decomposition temperature, and (d) volatility were obtained from references listed in the literature section of this report. It had been anticipated that these characteristics might differentially suit an odorant for either capsule, coating, cannister, or diaphragm use. For the most part, however, either the data were non-restrictive or were not available in the literature. All available data were used to eliminate inappropriate compounds from consideration. It is now believed that any further restrictions can best be found by empirical test.

Odorant Dispersion -- The odorant characteristics of (a) fire hazard, (b) explosion hazard, (c) toxicity, (d) corrosivity, (e) volatility, and (f) diffusion rate were also obtained from the listed chemical references. It was considered that these characteristics would bear on the problems of dispersion within and from the equipment, dispersion in the technician's area, and elimination, in a manner similar to container relevant characteristics. Available data did, in fact, enable elimination of many inappropriate odorants. Data on vapor pressure and diffusion coefficient were not available from the sources consulted, making volatility and diffusion rates impossible to calculate. Since these values are only loosely predictive of dispersion in any complex environment of air movement, it is recommended that empirical validation under known typical conditions be carried out before fact sheets on odorants can be satisfactorily completed.

Odorant and Perception -- Since the utility of an odor-coding system depends on a technician perceiving and identifying an odor, it is of prime importance to use odorants with characteristics that lend themselves to adequate perception. There are two hierarchical criteria for perception. The first is that an odor must be detected; the second is that an odor be identified.

Since discrimination of odor intensities has been seen to be more difficult (3 or 4 levels) than discrimination of qualities (16 or more), an odor code of quality is indicated to the exclusion of locating an odor source by its intensity. The problem of adaptation clinches this argument since perceived intensity might, at times, actually decrease as the odor source is approached.

We are left, then, with the necessity to establish only absolute thresholds at some high probability of detection. Identification of the odor is likely to require an even higher intensity level. Threshold data from the literature gives only a relative indication of an odor's intensity at best. In many cases, the overlap of different reported thresholds for two components will not even allow a ranking of their intensity characteristics with any certainty.

Adaptation rates are available for only a very limited number of odorous compounds. This is surprising since the utility of an odor could depend very much on the rate at which adaptation occurs for it if the rates are found to vary in considerable amount. Experts from such odor-dependent industries as the perfume industry appear to possess much more data than the scientific literature.

Industry experts also appear to have a greater wealth of information on odor qualities than can be found in the scientific literature. Together with absolute threshold, the quality distinctiveness of odors appears to be most critical when selecting an odorant for an odor-coding system.

Summary

In summary, it can be concluded that odor perception is a suitable medium for maintenance information, but the specific values for describing its use in quantified terms are lacking from the literature. Nevertheless, there are enough data to select apparently useful odorants for empirical testing. As these data are acquired, they may be presented in easily used matrix and/or tabular form.

SECTION V

GENERAL APPLICATION OF ODOR CODING

Introduction

The vast spectrum of Air Force systems provides a wealth of equipments and environments for possible application of odor coding to operation/maintenance activities. Some environments and/or classes of equipments are not as amenable to the application of odor coding as others. Discussed below are the considerations for application to Air Force systems and recommendations as to the systems and environments which most readily permit odor coding to be used effectively.

Air Force Systems

Types of Systems: Broadly speaking, the Air Force systems include the various "L" systems, missile systems, and aircraft "systems" with supporting ground equipment and test ranges, and space systems. Enumerated below is a list of systems which, though not exhaustive, covers the spectrum of the Air Force's systems.

A. Command, Control and Communication Systems

407L (TACS)	481L (PACCS)
410L	482L (EMS)
412L (AWCS)	484L (SOFTTALK)
413L (DEWLINE)	484N (PACS)
416M (BUIC)	486L (MEDCOM)
418L (RADS)	487L (SLFC)
425L (NORAD)	489L (NACS)
433L (METRO)	490L (AUTOVAN)
440L	492L (STRICOM)
465L (SACCS)	493L (VOCOM)
466L (ELINT)	494L (ERCS)
473L (HEADSHED)	495L
474L (BMEWS)	496L (SPADATS)
477L (NUDETS)	499L (AIMS)

B. Test Ranges

National Range Division (Eastern & Western Test Ranges)
Eglin AFB
Edwards AFB, Flight Test Center
White Sands

C. Space Systems

Satellite Control Facility
Atlas

Thor
Titan 3C
Agena (plus various payloads)
Manned Orbital Laboratory

D. Aircraft & Missile Systems & Associated Ground Support

Titan
Minuteman
B-52G-H, B-57, B-58
F100, 102, 104, 105, 106, 111, A-11
F4C, F9, F5
C-47, 123, 124, 133, 141, 5.

Classes of Equipment: There are many similarities in equipment among the various Air Force systems; for example, the "electronic" portion of the Command, Control, and Communications systems, space systems, test ranges, and the support equipment for aircraft and missile systems. Many of the Command, Control and Communications systems have antenna and receiving equipment as well as processing equipments, communications, and display equipment. Aircraft and missile support equipment frequently includes instrumentation using processing equipment, communications, and display equipments; test ranges and SCF are also quite similar in regard to kinds of equipments and to the equipments of the Command, Control and Communications systems.

Although subsystem equipment is frequently identified by a functional name, the classes of equipments listed below are included in all the ground support systems for missiles, the SCF for orbiting vehicles, the command and control systems with accompanying communication systems, and the test range instrumentation for aircraft, missiles, or space R & D operations.

Tracking equipments (antennas, receiving and/or transmitting equipment)

Receiving equipment

Transmitting equipment

R-F processing equipments

Digital/analog - analog/digital conversion equipments

Digital processing equipments

Computers

Communications equipments

Considerations for Maintenance and Operations

The application of odor coding to the detection/isolation of failures provides an "alarm" which is useful for both operations and maintenance activities. Although the emphasis of the study was primarily on maintenance activities, the role of odor coding for operations was also explored.

Maintenance Environments: Odor coding of failures is most applicable to environments that house equipments in buildings or vans or any enclosed, controllable environment. The dispersion of odors, regardless of release devices (see Section IV), cannot be controlled where air flow cannot be predicted. As a consequence, maintenance activities which take place on equipments in an uncontrolled environment are not amenable to odor-coding systems. (Although it may be possible in some cases to "remote" the odor to a favorable environment, the additional cost of such instrumentation in terms of money and/or reliability appears to preclude such a solution.) Summarized below are the considerations for odor coding in regard to the system/environments for Air Force systems.

- a. Command, Control, and Communications Systems. In general, odor coding as a maintenance aid is applicable to all of the Command, Control, and Communications systems. The classes of equipments have all the possible breakdown effects that can easily be used for initiating trigger mechanisms (see Section IV). The "environments" of the equipments are also favorable to the use of odor coding with the exception of antennas or antenna pedestals.
- b. Test Ranges. Odor-coding systems for maintenance activities on test ranges have the same applicability as for the Command, Control, and Communications systems.
- c. Space Systems. The ground portion of space systems like the SCF (stations and control center) and the command and control equipments supporting launches are directly comparable to the Command, Control, and Communications systems. The Agena (including payloads) and MOL do not lend themselves to odor coding; the former because maintenance is carried out in an uncontrolled environment (pre-launch checkout on launch pad) and no "maintenance" is carried on once the vehicle is airborne; the latter, MOL, does not currently lend itself to odor-coding systems even though "in-flight" maintenance may be performed. The present emphasis of no contaminants in manned vehicles seems to preclude the introduction of an odor-coding system.

However, odors can be selected which not only are non-toxic but also non-contaminating in the sense of introducing too "high" a number of particles per volume of "atmosphere" in

the vehicle. Since MOL astronauts will be "operator-maintainers," application of odor coding may be most beneficial -- while the auditory and visual senses are occupied in an operational task, the olfactory sense could be "free" for detecting impending failures and maintenance problems.

- d. Aircraft and Missile Systems and Associated Ground Support Equipment. In the main, only the electronic equipment associated with "central" checkout and launch control lend themselves readily to the incorporation of odor-coding systems. Maintenance activities on an actual "booster" or an aircraft is most often performed in an uncontrolled environment or an environment which, though controlled, is too far removed from maintenance or operator/maintenance personnel to be effective. Thus, the application of odor coding is best limited to those equipments which are housed rather closely together in a controlled environment, eg, launch control.

Operator Environments:

- a. Command, Control and Communications Systems. Although one could draw the distinction between operations and maintenance activities, it is too arbitrary for applications of odor coding to the Command, Control and Communications systems. All too often "operators" for the Command, Control and Communications system equipments are the first to detect "maintenance problems" and frequently aid in the isolation. For systems which have a 24-hour duty cycle for the "life" of the system, odor coding is particularly applicable. With around-the-clock visual/auditory monitoring, which is required for the majority of the systems, odor coding for the detection of failures is more applicable than to other operations. The loading of the visual/auditory senses makes the olfactory sense available for maintenance cues which may otherwise be missed until a catastrophic failure has occurred.
- b. Test Ranges. Although around-the-clock vigilance may not be the usual occurrence on a test range, there are many operations which require continuous vigilance for rather long durations -- pre-launch checkout is but one example. Again, odor-coding systems are quite likely a most worthwhile adjunct to the usual, or inadvertently, designed detection displays for incipient failures by equipment operator/monitors.

- c. Space Systems. Space vehicles, such as MOL, would provide an excellent opportunity for an experimental tryout of odor-coding systems for alarms or detection of impending failures. Barring the present position of not introducing even possible contaminants into a space vehicle, odor coding would seem to be most worthwhile for MOL, since astronauts will most frequently be heavily engaged in experiments requiring the closest of visual and/or auditory attention. The use of odor coding could be most effectively applied in such a situation -- a controlled environment in which the visual/auditory senses are heavily utilized.

The ground support of space systems is most analogous to the Command, Control and Communications systems. The increased workload of the support of orbiting of vehicles has meant that facilities such as SCF are rapidly approaching the 24-hour, everyday type of operation. The visual/auditory vigilance required of operators again makes the application of odor coding for incipient failures particularly attractive.

- d. Aircraft and Missile Systems and Associated Ground Support Equipment. The associated ground equipment of aircraft generally does not have "operators" and, consequently, the discussion concerning maintenance activities for ungrouped equipment in uncontrolled environments encompasses this class of equipment. One exception is flight simulators which have "instructor" operators in attendance. The environment and activities both provide a favorable setting for application of odor coding.

General Conclusions for Applications of Odor Coding

Applicability to Air Force Systems: Most Air Force systems, either in total or in part, provide an environment and equipments which readily permit the utilization of odor coding. The Command, Control, and Communications systems, the test ranges, the ground support systems for space vehicles, and some missile support systems are most appropriate.

Types of Operations. The application of odor coding is well suited for operations which require long duration vigilance and/or heavily engage auditory and visual modalities. Olfactory cues constitute a well coupled stimulus, similar to auditory cues, in that the sensory system need not be focused on the stimulus source. Thus, it is more likely that infrequently occurring events such as equipment malfunctions will be detected via the olfactory channel than, for example, the visual channel. The around-the-clock operations for the Command, Control and Communications systems and SCF (Satellite Control Facility) are particularly amenable to the use of another sense modality such as olfaction for the detection of impending

emergencies and/or failures. Odor coding need not be limited to the activities of maintenance technicians. Because of the design of the system and/or manning concept, the operators or operator/maintainers many times are the only ones available to detect failures. They take the first corrective actions -- switch to redundant equipment, enter different modes of operation, alert maintenance personnel, and describe the "trouble" or impending trouble.

With the exception of possibly introducing contaminants in manned aircraft and space vehicles, odor coding could be applied to equipment having in-flight "operators" and/or maintainers.

Types of Equipments/Environments: The application of odor coding is most easily adapted to equipments which provide breakdown effects that can, in turn, easily trigger odor release devices. In addition, these equipments should be housed in a controlled and predictable environment that includes either operators or maintenance personnel. Unattended equipments -- eg, equipment in a remoted antenna pedestal -- would require the remoting of an olfactory system back to an area where operator/maintainer personnel are located. Costs in terms of dollars and reliability of the over-all system are factors that decide against such an application.

Representative Equipments: The classes of equipment which are most amenable -- because of environment and/or breakdown effects -- to the application of odor coding have been listed earlier in the report. These equipments include both air/spaceborne as well as ground installations. The equipments may be packaged differently especially from air/spaceborne to ground installations and between installations, but this does not affect the application of odor coding to such equipments.

The Air Force Satellite Control Facility (SCF), consisting of a network of remote sites connected to a control center, and the test ranges have the same classes of equipments that are contained in Command, Control and Communications systems. Although the listed command and control and communications systems in totality are much larger than the SCF, the SCF or test ranges, because of their spectrum of classes of equipment in a central location, more easily lend themselves to a "tryout" of odor coding. The findings could be extrapolated to the command, control and communications systems because of similarities in classes of equipments, operating environments and operations.

Specific Types of Applications

An odor-coding system for detection and diagnosis is most applicable to those equipment subsystem and component failures which cannot be readily detected and diagnosed using present conventional procedures. We have already discussed the need for a maintenance analysis to evaluate the

desirability of adding odor indicators for each particular equipment system, and the extension of this analysis for establishing breakdown effects and selecting appropriate release devices. Consideration of the predicted outcomes of such analyses has permitted generalizations about the applications that can be expected from implemented odor-coding systems.

Equipment displays are typically established for the purpose of operations, and the use of these displays for maintenance purposes is sometimes considerably less than optimum. Failures may or may not cause changes in the operator's displays, and when they do, these changes may give little information concerning the subsystem or component that has failed. The addition of odor displays in such cases can shorten detection time and the time required for diagnosis. With as many as sixteen different odors each coded to a different function or physical location in the equipment, many steps can be saved from the diagnostic procedure by one act of odor identification. Such an odor-augmented display would be of special value in detecting failures that lead to cascading failures or function-critical failures before the secondary failure takes effect.

A promising application of odor coding is its use in the detection of incipient failures. Any technique that can give warning of an impending breakdown before any loss of function is incurred should receive a high priority of investigation. The basis of directing an application of odor coding to this purpose lies in the non-interference manner in which an odor-coding release device operates and in the non-interference type of signal produced. An operator or maintainer can continue to monitor and use conventional indicators for purposes of operation and failure detection while remaining free to respond to odor cues for detecting potential trouble before it shows up as an existing breakdown.

The major problem to be solved before this particular application can be recommended for broad scale implementation is a design and reliability engineering problem. At present, there is a limited technology covering the physics of failure (refs 72, 79). We need to determine and catalog the measurable effects that occur during the failure process for different components. Not only is this body of information presently small, but also the magnitude of the effect is typically small with a wide range of variation in the cases where data are available; therefore, it would appear that continued development of data and techniques for acquiring data are needed on a large scale. Also necessary is the continued development of sensitive and practical sensors for monitoring incipient breakdown effects in on-line equipment.

There are, nevertheless, some instances of incipient failures that do lend themselves to an odor-coding application. One example is the case of a drawer or rack of equipment that enters a slow failure process because of a rise in ambient temperature due to some overload, marginal ventilation design, or blower motor failure. It is recommended that such cases be exploited to stimulate increased interest in the problems of incipient failures.

Another specific application with high utility concerns low reliability components or subsystems as established by reliability predictions or early field data from new equipment. In the case of field data which indicates with some suspiciously high probability that a reliability problem exists, the flexibility of odor coding makes it especially suitable for interim use. The suspected equipment item can be odor tagged for quick detection and diagnosis during the period of time when a modification decision and its implementation are taking place. Selecting an adequate breakdown sensor for triggering odor release should be relatively simple since only one equipment item is involved.

Of the different kinds of equipment referents that might be used for an odor-coding system, it is possible to eliminate the alternative of component classes, such as resistors, diodes, etc. Having one odor represent, for example, all resistors would add nothing to the efficiency of the diagnostic procedure except for the last step of failure isolation. And this final part of the procedure usually takes place on the repair bench and not in the operational environment where odor coding would be used.

More appropriate referents are functional or spatial entities or a specific component which is critical to equipment operation. Using a functional entity as a failure referent is much more likely to result in a reduction of diagnostic steps, and therefore decreased maintenance time, than some grouping of similar components such as resistors. Diagnostic procedures typically follow an equipment function rationale since this approach lends itself to an ordered search for failures.

Similarly, using a spatial referent such as a drawer in a rack of electronic equipment can be expected to produce a substantial reduction in the steps required to isolate a failure by reducing the size of the search area.

Confirmation or rejection of these generalizations will need to be established by maintenance analysis and empirical test. Their present importance is as guidelines for formulating preliminary hypotheses about how to apply an odor code to an equipment system in order that substantial maintenance savings and improvement in equipment availability can be realized.

SECTION VI

RESEARCH RECOMMENDATIONS

Introduction

Sufficient information has been developed to indicate that odor coding could be used for aiding electronic maintenance in detection and isolation. However, the extent to which olfactory displays could enhance performance when added to traditional displays, ie, visual and/or auditory displays, has not been demonstrated nor is there any research in the literature which permits extrapolation as to possible enhancement. In addition, the literature reveals that research is also needed to arrive at optimum designs for an odor-coding system.

Over-all Research Requirements

The literature review has revealed that an odor-coding system is possible, although specifics for designing (and not over-designing) the system are not always available (eg, odorant requirements for .99 threshold). The next logical step is to empirically explore the effects of adding odor displays on the performance of some selected maintenance operations. If operational feasibility is demonstrated and performance is significantly enhanced, then the next steps would involve (a) the design definition and fabrication of prototype(s) for instrumenting an odor-coding system; (b) the necessary research to define design and application parameters for implementing any specific odor-coding system; and (c) the implementation of odor coding within specific Air Force systems. Research conducted within this framework would be most economical and expedient in arriving at a feasible working system which could be directly applied to either a new Air Force system or one that is being improved to meet new requirements.

Odor Coding/Maintenance Performance Study: The empirical study should be conducted in a realistic operational setting. This setting could be provided by actual equipment within operating Air Force systems or via valid simulation of all critical experimental variables. The requirements for such a study are outlined below.

- a. Maintenance Tasks. Although it may eventually be desirable to explore the dimensions of various types of maintenance tasks involving detection and isolation of faults, an initial study can be more limited and still demonstrate feasibility and effect on performance.
- b. Training of Subjects. Subjects should be selected from technicians who have had approximately equal experience on the chosen equipments. Odor training would involve individual subjects describing and labeling the odorants.

When "labels" had been derived for the odorants selected, training trials should be conducted until all odorants are correctly identified. This should take place after three or four trials.

- c. Selection of Odorants. Initial selection should be from the 16 groups identified in the literature review. Depending on test results prior to training, substitutions within groups of odorants may be made.
- d. Study Approach. A maintenance analysis of the selected equipments from a system should be made from the standpoint of adding odor release mechanisms. This analysis would utilize the available conventional analysis as a point of departure. Failure indicative components or equipment areas would be established, as well as function critical and low reliability components. The resulting identification of "faults" should be analyzed to insure a "non-destruct" and selected on a statistical basis to insure adequate samplings.

A complete behavioral record of maintenance activities should be taken during the test. These records, plus quantitative measure of performance and the maintenance analysis data, would permit full evaluation of the savings achieved by olfactory augmented maintenance displays.

- e. Study Constraints. Initial number of odorants should be kept small to stay safely within bounds of limits which exist for discrimination or learning to discriminate. Concentration of odorants should be high, and, at least for initial study, the "quick" elimination of an odorant need not be considered. (One fault would not follow another until facility ventilation had cleared odorant accompanying previous fault.)

Development of Engineering Designs and Prototypes: The initial performance study need not be ideally instrumented in the sense that such instrumentation could best suit actual implementation into any Air Force system. The triggering of release devices could, in a sense, be "simulated" for the performance study. If the study demonstrated enhanced performance, then such instrumentation should be developed and some prototypes fabricated. Many possibilities exist for instrumenting, such as encapsulated odorants, electrical or heat sensors, electro-mechanical or mechanical releases, "natural" dispersement, aerosol or spray devices, etc. Although these are possible, detailed engineering design is needed to arrive at economical and reliable instrumentation.

Research on Design and Application Parameters: The literature review revealed many shortcomings which, though not detrimental to an initial performance study, are detrimental to applications or to the extent of application for odor-coding systems. Areas of research, enumerated below, need not be postponed until after engineering designs of release devices, but can, and should, be accomplished in conjunction with the study outlined above.

- a. Determine threshold values for the .99 probability level. Our major concern is reaching an odor concentration that will enable detection and identification with a probability of at least .99 without producing an excessive concentration that would cause difficulties in odor elimination. Both within and between subject variability must be considered when establishing the necessary concentration level for an odor.
- b. Determine shape of the odor concentration curve plotted against subjective intensity. Since the complex conditions of an operational setting will not permit accurate control over odor concentration throughout the area of perception, it is important that the relationship between odor concentration and intensity be known for that portion of the curve in the vicinity of .99 probability of detection. If the curve is flat, adequate perception will be tenuous. Odorants whose subjective intensity rises sharply with increasing concentration levels are to be preferred.
- c. Determine objective measurements of odor concentration. It will be necessary to obtain measures of concentration independently of observer reports about odor in order that objective criteria can be established for concentration levels. An air sampling procedure at the point of detection appears to be most suitable for this purpose. The air sample can be analyzed in the laboratory to obtain the necessary concentration values.
- d. Determine extent of the effects of smoking, hunger, or nasal infections on thresholds. Although all of these variables have been shown to affect threshold values, it is believed that their effect is so small as to be negligible. Empirical validation of this belief would relieve any doubts that might be entertained.
- e. Determine adaptation rate for different odors at different concentrations. Adaptation could place an uncomfortable restriction on the amount of time available for detection and identification of odors. A rapid adaptation rate for an odor might necessitate increasing the concentration used to achieve .99 threshold.

- f. Determine recovery rate from adaptation for different odors and concentrations. Recovery time from adaptation would be a useful item of information since it would indicate how long a technician in an operational setting (or in a training session) must be isolated from an odor before his acuity returns to a high level of capability.
- g. Determine masking effects at various concentrations. Although the use of penetrating odors at sufficiently high concentration levels should minimize the masking problem, it is possible that some ambient odors from the equipment or its environment may interfere with discrimination among coded odors or even with detection. Likely masking odors such as rubber, insulation, or foods would be evaluated for their masking intrusion. Study of interference effects among concomitant coded odors would be deferred to a later stage of research since concomitant equipment failures are not anticipated as a likely event.
- h. Determine number of odors man can discriminate among and amounts of training required. The problem of how many odors can be used in the odor code is seen as consisting of two stages. The first stage is a confirming exercise to establish that as many as 16 odors can be used after a short period of training. The second stage is concerned with the amount of training time required to increase the number of odors substantially above this apparent plateau.
- i. Determine best labels to be used for describing odor qualities. There is some question concerning whether odor descriptors should be based on an individual, self-assigned procedure or should be established as universal standards. It is likely that a combination of these two points of view will prove to be most efficacious for efficient learning and communication.

It is recommended that items a, c, e, and f be studied first because of their criticality to design and implementation within a specific system.

Implementation for Specific Systems: With favorable results from the performance study, research on design and application parameters, and engineering design of instrumentation for odor coding, the obvious next step is implementation to an Air Force system. Sufficient information will exist for writing specifications for an odor-coding subsystem. The performance specification could then be incorporated as part of the System Specification for either a completely new system or new subsystems when improving on existing systems.

The final phase of the research recommendations would be the development of a Performance Specification for odor-coding systems and specific design guide information regarding specific applications and engineering solutions in implementing the system.

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DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1 ORIGINATING ACTIVITY (Corporate author) Philco Corporation, Western Development Labs. Palo Alto, California 94301		2a REPORT SECURITY CLASSIFICATION UNCLASSIFIED
		2b GROUP N/A
3. REPORT TITLE ODOR CODING FOR MALFUNCTION DETECTION AND DIAGNOSIS		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final report, May 1965 - March 1966		
5 AUTHOR(S) (Last name, first name, initial) Goldbeck, Robert A., PhD Kaeding, Judith H. Feroglia, W. E.		
6. REPORT DATE August 1966	7a TOTAL NO OF PAGES 56	7b. NO OF REFS 99
8a CONTRACT OR GRANT NO. AF 33(615)-2948 b. PROJECT NO. 7184 c. Task No. 718406 d.		9a ORIGINATOR'S REPORT NUMBER(S) 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AMRL-TR-66-122
10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited.		
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Aerospace Medical Research Laboratories, Aerospace Medical Div., Air Force Systems Command, Wright-Patterson AFB, Ohio
13. ABSTRACT The use of the olfactory sense for detecting and diagnosing malfunctions in equipment systems has been investigated. The literature on olfaction is reviewed and the data and data gaps relevant to equipment maintenance applications are summarized. With the literature findings as a point of reference, performance requirements for an odor-coding system are established and a taxonomic structure is synthesized for the purpose of developing specific odor-coding systems. A survey of equipment system applications leads to the conclusion that odor-augmented maintenance displays are both feasible and practical. Recommendations are made for a program of research and development leading to broad scope implementation of odor coding for malfunction detection and diagnosis.		

KEY WORDS

Odor-coding system
 Odor stimuli
 Olfactory thresholds
 Malfunction detection
 Maintenance cuing
 Perception
 Identification
 Performance requirements

LINK A

LINK B

LINK C

ROLE

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